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ON A GLOBAL AERODYNAMIC OPTIMIZATION OF A CIVIL TRANSPORT AIRCRAFT

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ABSTRACT

An aerodynamic optimization procedure, dedicated mainly to minimize the drag to lift ratio of a complete configuration: wing - body - tail, in the presence of some engineering and logical restrictions is described. An algorithm conceived to search the minimum of a hypersurface with 18 dimensions, which define an aircraft configuration, was developed, without using a gradient method. The obtained results, show that, at least, from the aerodynamic point of view, the optimal configuration is one of canard type, with a lifting fuselage.

I. INTRODUCTION

There are many arguments which plead for the using of a global and multicriterial optimzation procedure to design a transport aircraft. An usual practice, for the establishment of the aircraft's shape, adopted especially by the prudents, is the statistical processing of the data describing all the aircrafts of that class. Finally, after years of research, design, manufacture, testing and certifying, an out - of - date aircraft results, at least with two generations behind: one which was in service when the design of the new aircraft begun, and the second, which started at the same time, but has used the latest research results correctly forecasted.

To predict exactly the needs in the domain of passengers air transport, for the date when the new built aircraft will operate, taking into account all the economical, social and scientific conjunctures, a global and multicriterial optimization procedure is required. A new aircraft becomes competitive versus other aircrafts of its class, if the fuel consumption reduction is obtained not by affecting the passengers security and comfort and by adding laborious maintenance operations. Following these principial ideas, in the present paper we have tried to optimize, only from the aerodynamic standpoint, a short / medium - currier configuration aircraft for moderate subsonic speeds.

Here, by "optimal configuration" we understand the configuration which gives the best answer to a certain purpose. A more realistic objective function to be minimized in the presence of the engineering and airworthiness requirements, can lead to a competitive aircraft, providing benefits, both for passengers and companies.

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Another argument which demands the adoption of a global optimization procedure in the design process is the paradox, valid at least as far as our personal experience is concerned, that while aerodynamics, thermodynamics and stress analysis use the most sophisticated computing methods, their results are used mainly to decide whether a previously shaped by an "all experienced" project authority configuration is competitive, and not from to begining in the process of giving that configuration the best shape for a certain purpose.

II. THE AERODYNAMIC ANALYSIS

For the global aerodynamic characteristics (CL, CD, Cm) of a complete wing - body - tail configuration, a panel method [1] was used. Two rather hard approximations were adopted in order to ensure minimum CPU time for the analysis procedure:

a) Following the idea introduced in [2], the configuration is replaced by its horizontal projection (plane xOy "shadow"). The entire thin surface of this projection is divided into a number of triangular or quadrilateral panels, associated, each of them, to a horseshoe vortex filament.

b) For the friction drag, the flat plate assumption is adopted and consequently, on the wetted area the friction coefficient Cf is calculated as a function of the Reynolds number on each surface strip (without detachment).

The theoretical results obtained on the idealized configuration of Fig. 1.b. were compared with the experimental data measured in the Trisonic Wind Tunnel of the Aviation Institute of Bucharest, Romania, on a calibration model (Fig. 1.a).

The comparative diagrams CL, CD, Cm versus incidence (Fig.2) demonstrate that, in the domain of the small incidences, the analysis is in good agreement with the experiments. This meets our interest because the above - mentioned optimization will be performed at the cruise regime.

III. THE OPTIMIZATION PROCEDURE

Considering the results of the aerodynamic analysis as acceptable, the corresponding algorithm can be included into an optimization loop.

A generic aircraft configuration was defined by 18 geometrical parameters (Fig. 3) as follows:

x1 - the span of the surface I
x2 - the chord ratio of the surface I
x3 - the root chord of the surface I
x4 - the span of the surface II
x5 - the chord ratio of the surface II
x6 - the logitudinal position of wing apex
x7 - the logitudinal position of the horizontal tail apex

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x8 - the wing span
x9 - the wing chord ratio
x10 - the chord ratio of the horizontal tail
x11 - the span of the horizontal tail
x12 - the wing sweep angle
x13 - the horizontal tail sweep angle
x14 - the root chord of the horizontal tail
x15 - the incidence of the surface I
x16 - the incidence of the horizontal tail
x17 - the wing incidence
x18 - the root chord of the wing

The geometrical characteristics of the vertical tail and the dihedral angle of the wing were done as input data.

The incidence of the surface II was assumed equal to that of the surface I.

These 18 parameters are the 18 dimensions of a hypersurface, described by the objective function "F" which represents a sum of criteria of minimization.

Performing a statistical evaluation over a class of 30...50 passenger aircrafts, the overall mass of an aircraft was deduced to be estimated by:

$$G = 100*Npax + Ka*Sa + Kt*(Sht + Svt) + Kf*Sf + Goi \qquad (1)$$

where:

Npax - the number of the passengers
Sa - the effective wing area
Sht - the effective horizontal tail area
Svt - the effective vertical tail area
Sf - the xOy projected area of the fuselage
Goi - the inert mass of the aircraft (≅ 7700 daN for a 50 pax. and = 5500 daN for a 30 pax. aircraft)
Ka - the specific weight of the wing (≅ 58.3 daN/m)
Kt - the specific weight of the tails (≅ 33.8 daN/m)
Kf - the specific weight of the fuselage (≅ 40 daN/m)

In the present study the criterion of optimization was related to the minimizaton of the CD/CL ratio satisfying simultaneously the following constraints:

- the pitching moment My with respect to the gravity center must be zero or very close to this; the position of the gravity center is recalculated every time the configuration changes.

- the lifting force must be equal to the overall weight of the airplane in cruise flight.

- the position of the wing and tails apexes must be located within the fuselage length.

- because "in an aircraft, the main part of the structure's weight is given by the material which ensures the

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bending moment at the wing-body embeding" [3], an important restriction was to put a limitation on the bending moment at the wing-body junction. In the absence of this constraint the wing has the tendency to get a quite large aspect ratio, typical for sailplanes.

There are many objective functions Fi(X) for a class of aircrafts which can be minimized or maximized. For example, [4], with only four parameters (wing area, sweep angle, aspect ratio and the relative thickness of it's airfoil) a configuration was optimized with four objective functions:

F1(X) - ramp weight (minimize)
F2(X) - mission fuel (minimize)
F3(X) - lift to drag ratio at constant cruise Mach number (maximize)
F4(X) - range with fixed ramp weight (maximize)

or some combination of these objective functions.

Mathematically the optimization procedure means to search and find the minimum of the above-mentioned hypersurface in the presence of a number of given restrictions. The minimization problem with the restrictions "g(X)" is transformed into one without restrictions using "the penalty functions method" [5]. Each restriction is associated with a penalty function. If one restriction is violated, the corresponding penalty function is set to a great value; thus the objective function becomes greater (far from minimum). If the restriction is satisfied, the penalty function is set to zero: so it doesn't affect the value of the objective function F(X).

$$F(X) = CD/CL + \sum g_i(X) = \text{minimum} \qquad (2)$$

$$X = X(x1, \ldots, x18) \qquad (3)$$

For the effective searching of the minimum of the objective function F(X) the "one dimensional searching method" was adopted [5].

First, for the "starting configuration" (meaning the configuration determined by the initial values of the 18 optimization parameters) a first value of the objective function is calculated.

Than, one of the parameters is altered by a step "r", while all the others are kept constant:

$$x_i = x_i + r.x_i \qquad (4)$$

$$0 < r < 1$$

The aerodynamic analysis module is called and the value of the objective function F(X) is computed. If its value is smaller than the previous one the alteration of the parameter "x_i" is continued until the value of F(X) begins to rise. In that moment the parameter x_i is altered with $-r.x_i$ and the process of parameter x_{i+1} alteration is initiated (Fig.4). When the optimization loop, containing all the 18 parameters is ended, the procedure is repeated with

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a refined r, as long as r is superior to a selected error level.

The major disadvantage of this method is that a local minimum is usually reached by altering only some of the parameters and it is almost impossible to leave it. Besides of the parameters hierarcy, which is not so easy to establish, the procedure was modified in two different ways, in order to avoid the local minima:

a. At a certain value r the steps towards the minimum were limited at only two per parameter, even if the value of the objective function is still decreasing (Fig.5a).

b. For every parameter the sign of r is determined for which the objective function F(X) decreases. Then, all the parameters are simultaneously altered as long as F(X) decreases. When an increase in the value of F(X) is noticed the sign determination process is initiated again, followed by another phase of block alteration of all the parameters (Fig.5b). In this way, the aerodynamic analysis module is called once for a configuration resulted from the simultaneous alteration of all the parameters, thus saving computer running time. This modified version of the optimization procedure is somewhat similar to a gradient method but it doesn't need the calculation of the parameter's gradient vector.

IV. RESULTS AND DISCUSSION

The optimization procedure described above was transferred into a FORTRAN computer code and several tests were performed to certify its validity.

Among these tests, for example, the "FOKKER 27 - Friendship" airplane, quite repreentative for the 50 seats class, was adopted as a starting configuration in the idealized manner represented in Figure 6, by the lowest possible number of panels, to permit a fast aerodynamic analysis.

Denoting by "classic configuration" the wing-tail arrangement in which the wing is placed ahead of the tail and by "canard configuration" the well known tail in front of the wing arrangement, the optimzation computer code was applied and the results finally obtained are illustrated in Figures 7-9.

It can be noticed (Figure 7) that the aerodynamic (CL - CD) characteristics of the classic-optimized configuration are not much different from those classic - initial configuration, this proving that the F-27 airplane is aerodynamically well designed.

In the same time, the canard - optimized configuration has obviously superior aerodynamic characteristics, when compared to the initial (unoptimized) canard configuration (Fig. 8) and even compared to the classic - optimized configuration (Fig. 9).

During the optimization process an interesting fact was considered to be the tendency of the fuselage to widen its rear end, taking a shape somewhat similar to a small aspect ratio gothic delta wing, thus increasing its contribution to the global lift of the airplane.

We must stress that the aerodynamic analysis module and even the optimization algorithm used in the optimization procedure ex-

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empled here are, of course, not the best tools according to today's achievements, and any improvements in these directions could lead to better results at the end of an optimzation loop. Our choice was determined by the inherent limitations set by the presently available to us, computer equipment.

The CYBER 170/720 computer was used to perform the calculations which lead to the results presented here. A single call of the aerodynamic analysis module requires about 3 seconds CPU time for an idealized configuration of 40 panels (Fig. 6). To reach the optimum shape, at the moment when the relative error on "r" is less than 0.0001, some 260-300 calls of the aerodynamic analysis module are usually necessary.

The optimization code was used to define some of the principal features of the external shape for a few other short/medium range commuters.

Such an example, reffering an airplane with a 70 passengers capacity, flying at 650 km/h, 6000 m of altitude, is represented in Figures 10 a,b. The thickness was added to complete the shape of the idealized optimum configuration. Such a "thick" configuration is suitable for a much more accurate aerodynamic analysis, performed with better computer codes and even in the wind tunnel, in order to obtain a realistic final verdict on the optimization procedure and its results. The rear end wide fuselage is quite noticeable. Apart the aerodynamic gains, this type of fuselage can provide the passengers a better comfort, giving the opportunity for a cabin arrangement similar to that of a wide body airplane (Figure 11).

An indirect confirmation of these solutions, analysed since 1988, [6], was offered by a recently published paper [7], which reportss that studies are made to use an elliptical fuselage for a long range, high capacity airliner.

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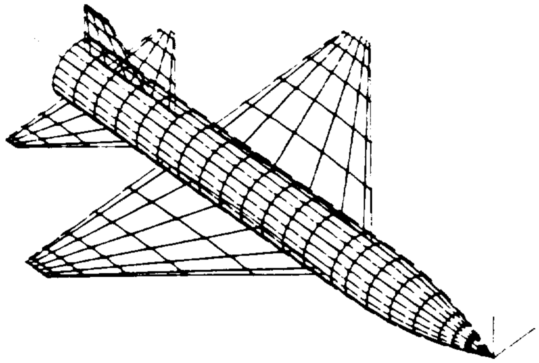

Fig.1.a. The calibration model for wind tunnel testing.

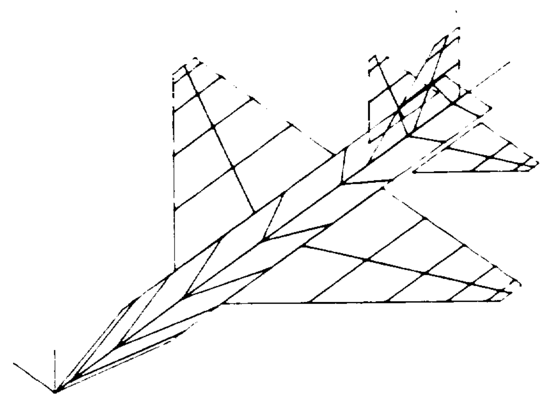

Fig.1.b. The idealized geometry for panel method calculation.

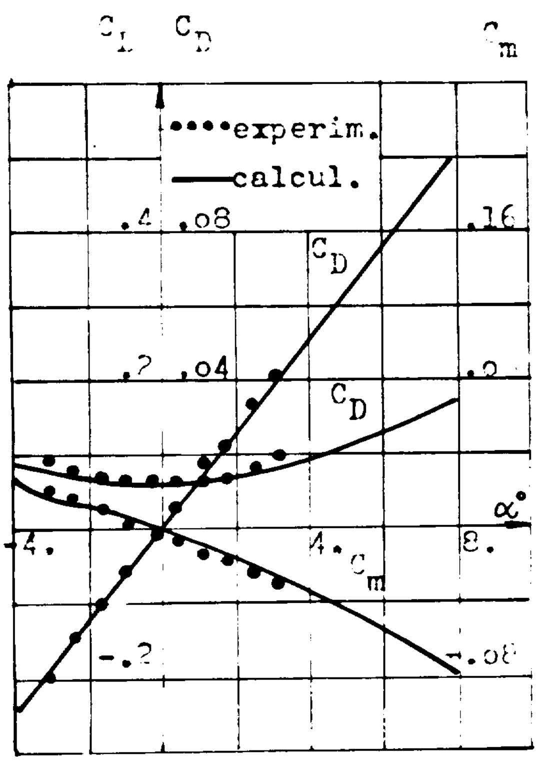

Fig.2. Comparison experiments-theory for test case 1.a. b. (Mach=0.304, MRe=4.26).

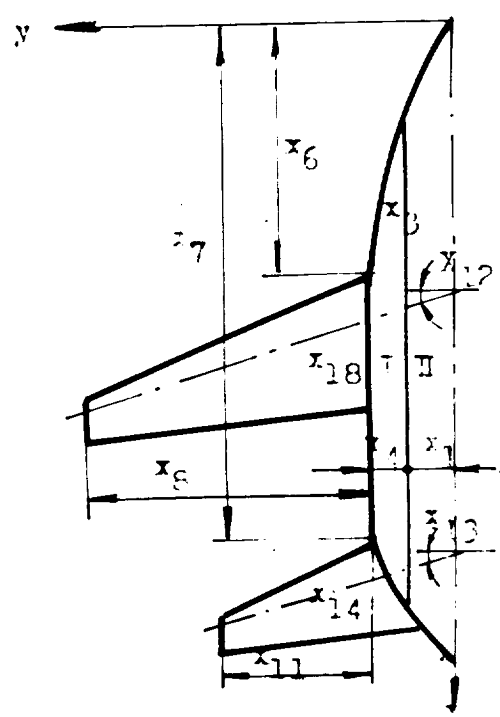

Fig.3. A generic configuration defined by 18 parameters.

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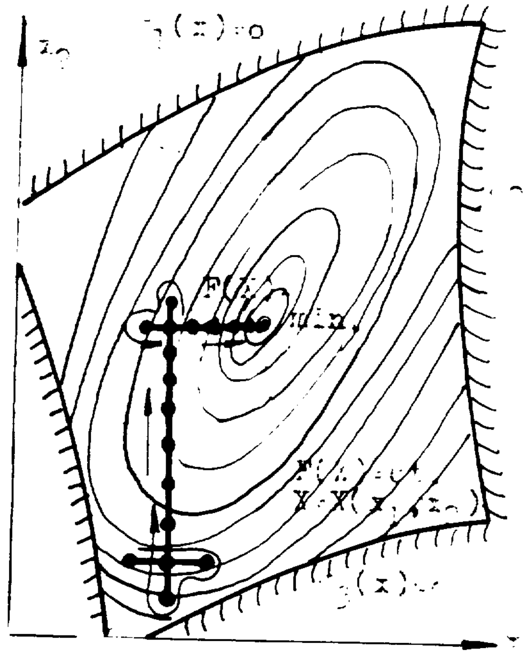

Fig.4. The "one-dimensional minimum searching"procedure with restrictions(2-D case)

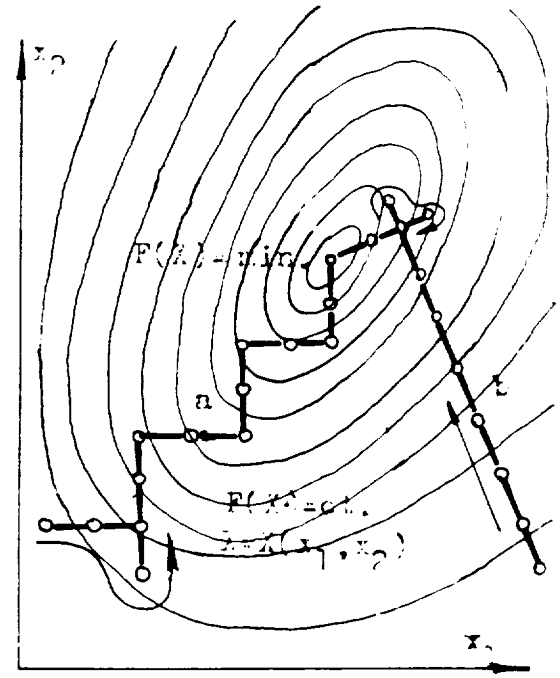

Fig.5. The modified (a,b) "one dimensional minimum searching" method (2-D case).

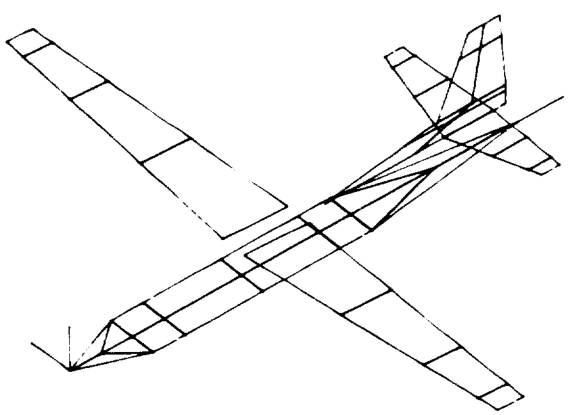

Fig.6. The "F-27" idealised configuration for the aerodynamic analysis.

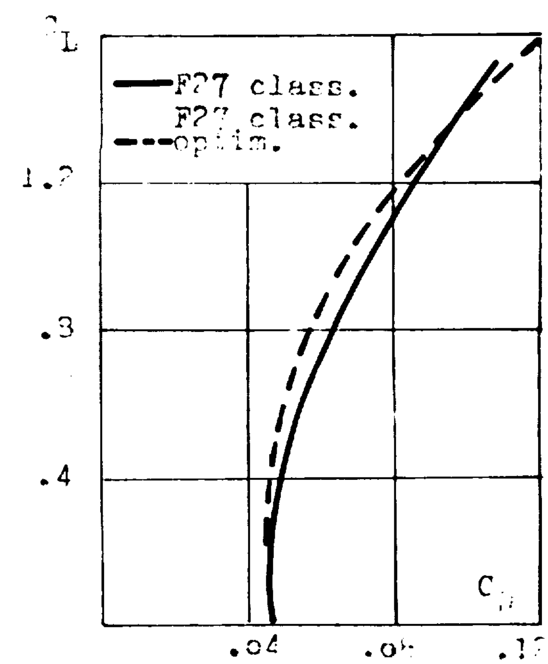

Fig.7.The comparative characteristics of "F-27"classic and "F-27"classic - optimized.

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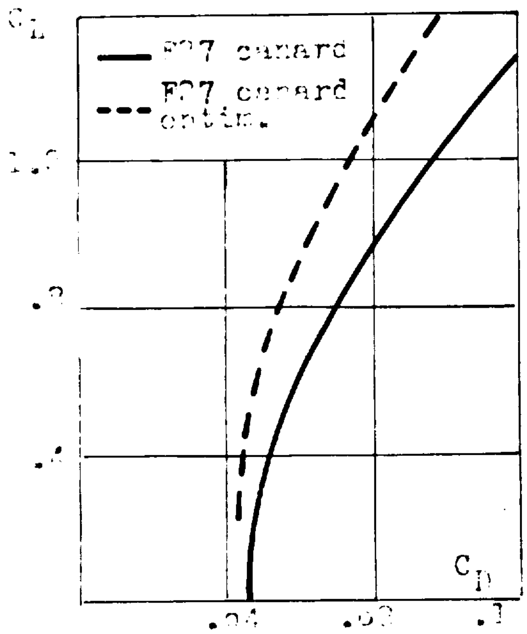

Fig.8.The comparative characteristics of"F-27"canard and "F-27"canard-optim.

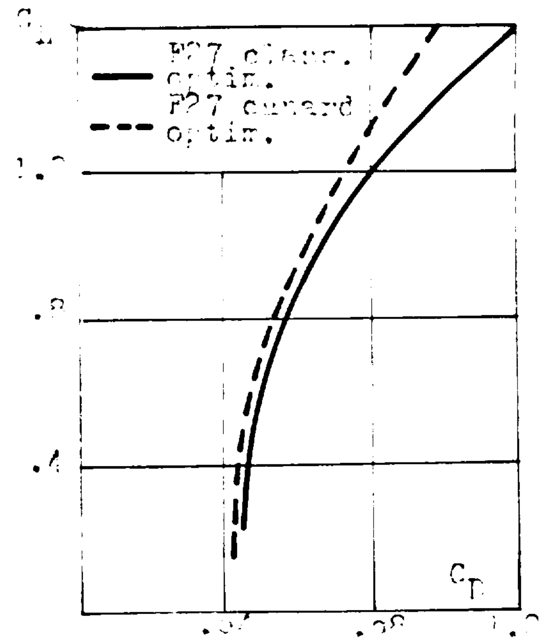

Fig.9. Comparison of "F-27" canard - optimized and "F-27" clasic - optimized.

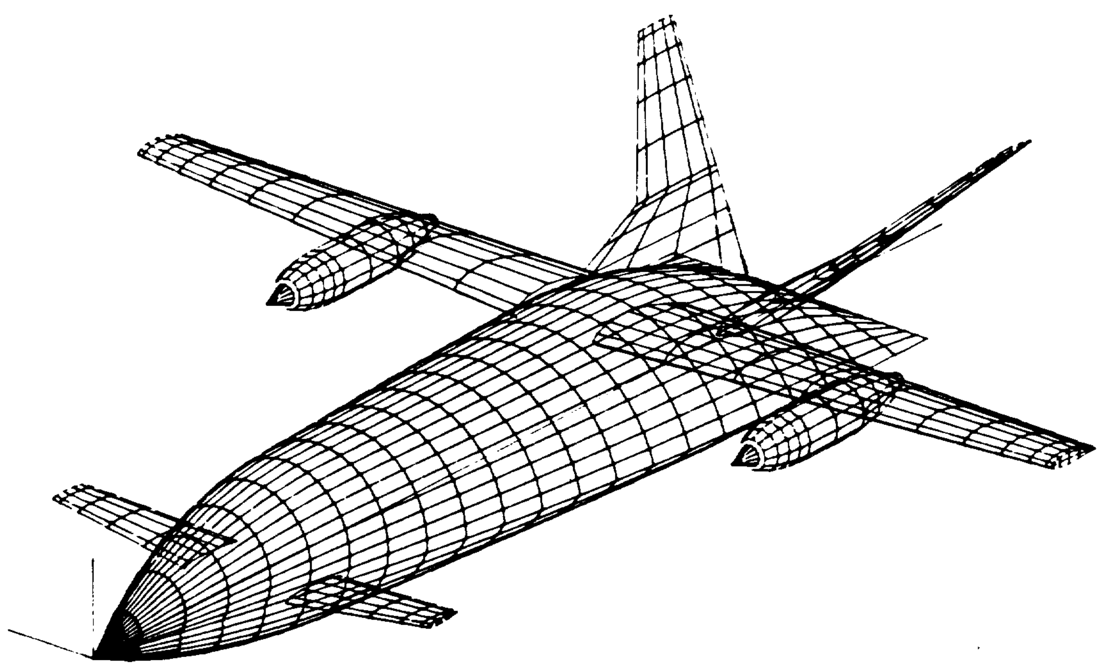

Fig.10. General view of an optimized short/medium currier (70 pax. capacity, V=650 km/h)

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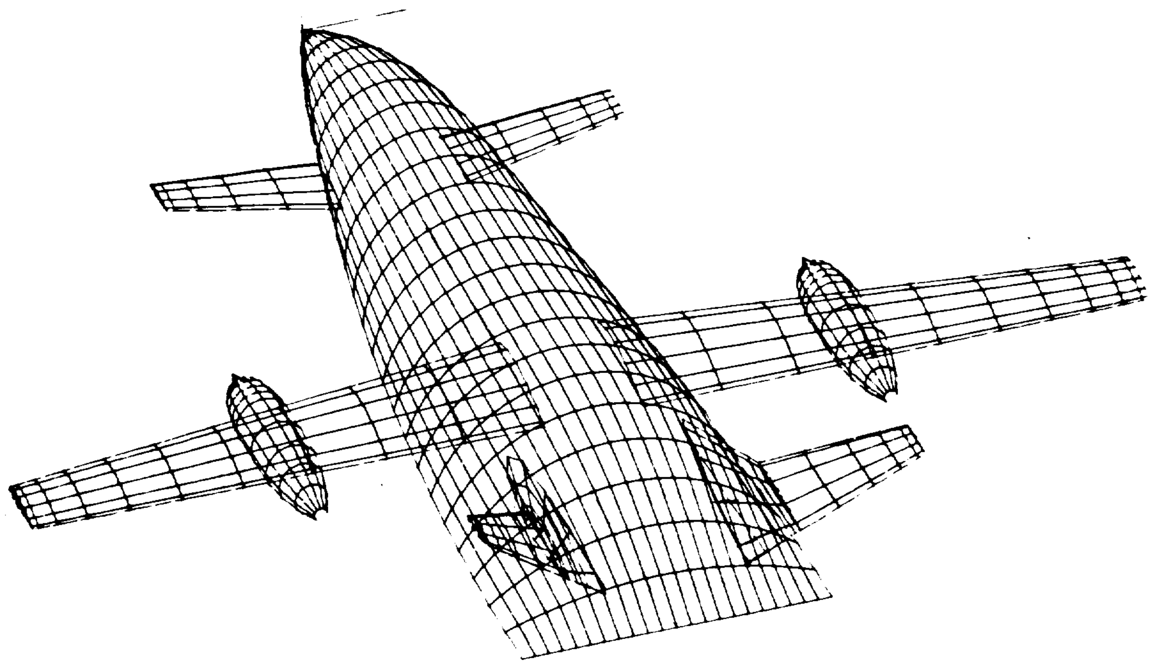

Fig. 10.b Another general view of the optimized configuration of Fig. 10.

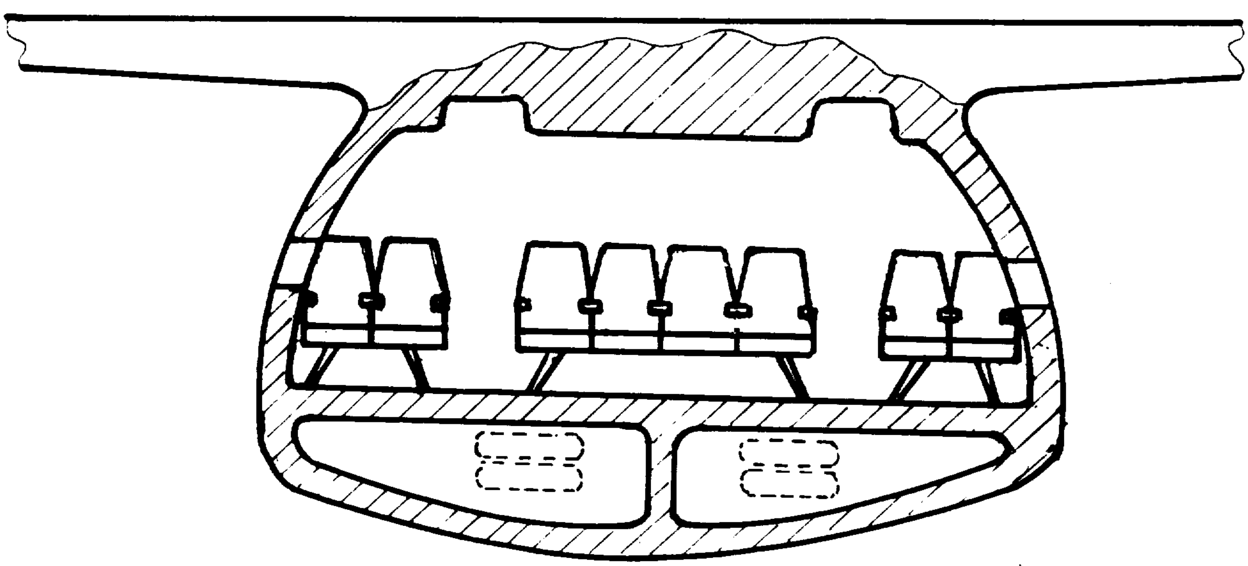

Fig.11. A possible seats arrangement in a cabin of an optimized short/medium currier airplane.